Bottom Boundary Layer Processes Associated with Fine Sediment Accumulation: Application to STRATAFORM

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LONG-TERM GOAL

The global objective of the Virginia Institute of Marine Science (VIMS) involvement in the STRATAFORM program is to improve understanding of the spatially and temporally varying mechanisms that suspend, transport, and deposit sediment specifically on the continental shelf in the vicinity of the mouth of the Eel River and generally on continental shelves that are accumulating fine sediment.

SCIENTIFIC OBJECTIVES

Specific objectives of VIMS involvement in STRATAFORM Phase I and II were to observationally characterize the spatial and temporal variability of bed roughness, bed stress, sediment resuspension and sediment flux at multiple sites on the Eel River shelf. During Phase III (October 1998-October 2000) our primary aim has been to synthesize our field results with other STRATAFORM investigators in order to help answer four of the six essential questions identified at the 1998 STRATAFORM Keystone meeting for the final phase of the program's shelf component: (1) How is sediment that is lost from the plume moved seaward to the mid-shelf mud deposit? (2) What are the magnitudes and mechanisms of storm- and flood generated sediment fluxes in the along-shelf direction? (3) How do flood deposits evolve in response to physical and biological reworking? (4) What is the "skill" of Eel shelf models in predicting relevant processes in other fine grained depositional systems?

APPROACH

Our approach in Phase I and II involved field observations of bed micromorphology, benthic flow, bed stress, suspended sediment concentration and suspended sediment flux on the northern California continental shelf north of the Eel River mouth. Over the late fall and winter of 1995 to 1996, we obtained regional measurements of bottom roughness via side-scan sonar and via profile and surface camera images of the sediment-water interface. We deployed fully-instrumented bottom boundary layer tripods on the “S” line at depths of 60 m and 70 m in January and February 1996, during which time two high energy events occurred. The tripods were re-deployed on the “G” line at depths of 30 m and 60 m from November 1996 to January 1997, a period that included a major flood event. Our approach in Phase III was to further develop and apply asymptotic analytical relations which highlight the most important mechanisms for fine sediment suspension, transport and deposition acting on the Eel River shelf. This approach provided a conceptual bridge between environmental forcing and the output of more complex numerical models.

WORK COMPLETED

Field data collected by VIMS investigators has been published as VIMS data reports (Wright et al. 1996; Hepworth et al. 1997) and also on the VIMS STRATAFORM website: http://www.vims.edu/physical/strataf/strataform.htm. Analysis of bed micromorphology has been published as a Masters Thesis (Cutter 1997) and associated camera images are available on the web at http://www.vims.edu/~cutter/st95spi.html. Data reports, including data summaries on diskettes were prepared and distributed to interested STRATAFORM participants as soon as initial analyses and data quality assessments were completed. Some initial results from the first field experiment were reported by Wiberg et al. (1996). A paper detailing the results of the tripod measurements from the first VIMS field deployment appeared in the STRATAFORM special issue of Marine Geology (Wright et al. 1999). A paper interpreting the micromorphology and biological alteration of the upper seabed observed during the first field experiment has been published in Continental Shelf Research (Cutter and Diaz 2000). The ease with which our group made VIMS tripod data from this first deployment available to other investigators in STRATAFORM is illustrated by its preferential use in the initial calibration of numerical models by groups that did not include field specialists (Morehead and Syvitski 1999; Reed et al. 1999; Zhang et al. 1999). A paper detailing the results of the second VIMS field deployment has recently appeared in Continental Shelf Research (Friedrichs et al. 2000a). Our work as part of STRATAFORM Phase III has been submitted to Marine Geology (Wright et al submitted), is the subject of a Masters Thesis nearing completion (Scully in prep.) and will also be presented at the Fall 2000 AGU meeting (Friedrichs et al. 2000b; Scully et al. 2000; Wright and Friedrichs 2000; Wright et al. 2000).

RESULTS

The results of our first field experiment (Wright et al. 1996, 1999; Cutter and Diaz 2000) include interpretation of bottom images and tripod time-series. Based on image data from December 1995, three regions along the “S” line were defined: inshore shelf sands, a transitional region where sands transported by storms alternate with flood beds, and mid-shelf flood deposits. The degree of bioturbation was highest in the flood deposit region where burrows, the surface unconsolidated layer, active and relict feeding voids, and animals were more prevalent. In the transitional zone, there was evidence for both shallow and deep infaunal activity, but also apparently less utilization of the storm sand layer, suggesting that the infaunal community has adapted to the combined influence of deposition and storm transport. Tripod data along the “S” line documented two high energy events between January and March 1996, with near-bed suspended sediment concentrations 15 cm above the bed reaching 2 g/l. At these times, suspended sediment induced stratification significantly suppressed near-bed turbulence within the current boundary layer. The abundance of under-consolidated fine sediment on the shelf to the north of the Eel River presumably allows increases in stress to be accompanied by progressive increases in suspended sediment concentration within the lowest meter of the bottom boundary layer, causing the gradient Richardson number to remain near the critical value of 1/4. The analyses of our second field experiment at 60 m along the “G” line (Friedrichs et al. 2000a) also highlighted the role of sediment-induced stable stratification affecting the structure of the bottom boundary layer. Observed semi-log velocity profiles were (1) concave downward, (2) straight, or (3) concave upward depending on whether the sediment-induced density anomaly decreased with height above the bed (1) much more slowly than, (2) at roughly the same rate as, or (3) much more rapidly than (height above the bed)$^{-1}$.

As part of our Phase III work, we have performed a comparative analysis of bottom-boundary-layer velocity profiles, bed stresses and suspended sediment concentration profiles that we have measured in five contrasting shelf and semi-enclosed bay environments that are presently accumulating fine sediments (Friedrichs et al. 2000a; Wright et al. submitted). The sites are: the northern California shelf off the mouth of the Eel river; Eckernförde Bay, southern Baltic Sea; the York River estuary, lower Chesapeake Bay; the Louisiana shelf to the west of the Mississippi River mouth; and the Gulf of Bohai off the Yellow River. At these sites, the presence of density stratification caused simple fits of log profiles to velocity observations over the lowest meter to overestimate bottom stress. Stable stratification was attributable to a combination of suspended sediment and thermohaline effects, with the former and latter dominating under high and low energy conditions, respectively. At all sites, the near-bed gradient Richardson number approached or exceeded the critical value of 1/4 implying that turbulence was damped by stable stratification. At the majority of these sites, down-slope transport of fine sediment was inferred due to the interaction of gravity and suspension by ambient currents.

During Phase III we have developed asymptotic analytical relations for critically stratified bottom boundary layers characteristic of the Eel Shelf, applicable within the current boundary layer and also within the underlying wave-boundary layer (Wright et al. submitted; Friedrichs et al. 2000b). When strong waves suspend abundant, easily eroded fine sediment to concentrations approaching fluid mud within the wave boundary layer, concentration gradients become sufficient to maintain Ri near its critical value of 1/4 within the overlying current boundary layer. The resulting velocity profiles within the current boundary layer are very nearly logarithmic even though the Karman-Prandtl equation no longer applies. We have developed a simple analytical theory to derive mean current stress and sediment flux from such velocity profiles without requiring any information regarding sediment properties. Figure 1 compares observed and predicted sediment flux within the current boundary layer at S60 based only on observed currents and the assumption that Ri = 1/4 (Friedrichs et al. 2001).

Most recently, our Phase III work has focused on the role of hyperpycnal (denser than ambient water) plumes in generating gravity-induced across-shelf sediment transport (Wright et al. 2000, 2001; Friedrichs et al. 2001; Scully et al. 2001). Observations from California, Louisiana, and the Gulf of Bohai were shown to be consistent with simple analytical theory for down-slope gravity-driven transport that incorporates the influence of ambient shelf currents (including waves) on hyperpycnal plumes. If the supply of easily suspended sediment is less than the capacity of ambient waves and currents to suspend sediment, intense turbulence limits gravity-induced sediment transport by increasing the drag at the plume base. When ambient currents abruptly cease, rapid down-slope flow can then occur over short distances as the sediment settles. Such flows do not remain turbulent because the slope of the continental shelf is too gentle to allow autosuspension. The maximum sustained rate of gravity-induced sediment transport occurs when ambient currents are strong, but the supply of easily suspended sediment still exceeds the suspension capacity of the flow. Feedback then favors Ri within the plume to be near its critical value of 1/4. This partially damps bottom drag, but permits sufficient turbulence to maintain suspension within the plume.

The analytical solution for critically-stratified gravity currents predicts sediment load, hyperpycnal plume speed and down-slope sediment flux without needing specific information about sediment properties. Figure 2 compares the observed and predicted downslope plume velocity at the top of the wave boundary layer at S60 (observed currents from Ogston et al. 2000) using only observed wave height and along shelf current velocity as inputs (Scully in prep.). If waves are the dominant source of bottom stress, which is often the case on the Eel shelf, deposition rate as a function of distance across the shelf can be predicted based only on knowledge of wave height, period and river sediment discharge. Figure 3 displays deposition predicted for an idealized Eel River shelf (no along-shelf variation in slope) integrated over time for the 1995 and 1997 flood seasons (Scully in prep.). The thickness and across-shelf location of the predicted deposits in Figure 3 are similar to that observed by STRATAFORM investigators soon after each of the floods.

IMPACT/APPLICATIONS

Measurements of near-bottom processes at different depths on the shelf provide insights into the mechanisms responsible for along-shelf and across-shelf sediment suspension and transport, the sources and nature of across-shelf variations in bottom stress and hydraulic roughness, and the causes and magnitudes of the across-shelf gradients in sediment flux that may contribute to sediment deposition. The results from the STRATAFORM site, when compared with other sites that are accumulating fine sediment, have yielded new generic insights concerning differences between bottom boundary layer processes in such environments and those that prevail on sandy shelves. Two of the marked differences highlighted to date by our results are the important role of suspended sediment in suppressing turbulence on shelves accumulating fine sediment and the significant role of gravity-induced hyperpycnal plumes in modifying the nature of across-shelf sediment flux. Our results are being applied to develop modified models for transport of highly concentrated fine sediment over soft, easily eroded beds.

TRANSITIONS

Our data on bed stresses and resulting sediment resuspension have been made available to modelers and other STRATAFORM investigators and are being used to verify bottom boundary layer and sediment transport models. Our data can easily be accessed via data reports (which include data summaries on diskettes) and via the VIMS STRATAFORM website. Published papers by others which have directly utilized VIMS data include Morehead and Syvitski (1999), Ogston et al. (1999, 2000), Reed et al. (1999) and Zhang et al. (1999). Several additional papers by non-VIMS authors incorporating VIMS data are in preparation. Over the next two fiscal years, our analytical formulations for sediment flux and deposition by critically-stratified, gravity-induced hyperpycnal plumes will be incorporated into long-term simulations of margin stratigraphic development by ONR-funded investigators, both within and outside VIMS.

RELATED PROJECTS

The following projects involving Friedrichs and/or Wright also address fine sediment transport and accumulation in coastal environments:

1. Biological Mediation of Bottom Boundary Layer Processes and Sediment Transport in Estuaries. Office of Naval Research (Harbor Processes).

2. Physical and Biological Mechanisms Influencing the Development and Evolution of Sedimentary Structure. Naval Research Laboratory (Coastal Benthic Boundary Layer SRP).

3. Sediment Dynamics of a Microtidal Partially-Mixed Estuary. National Science Foundation (Marine Geology and Geophysics).

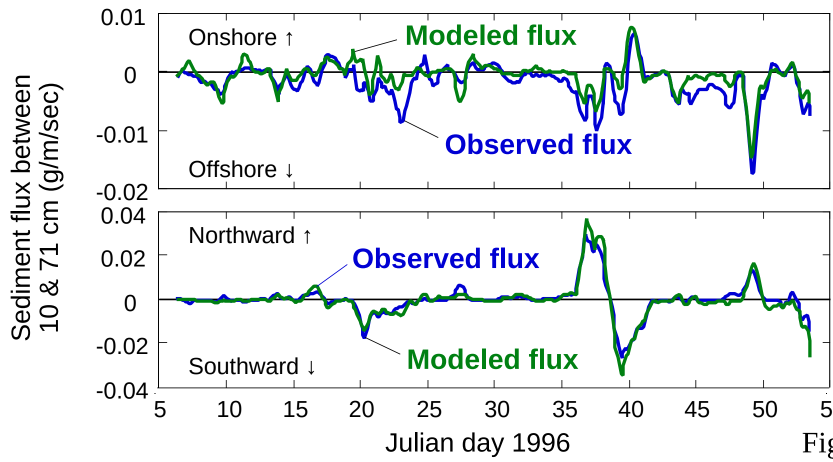

Figure 1

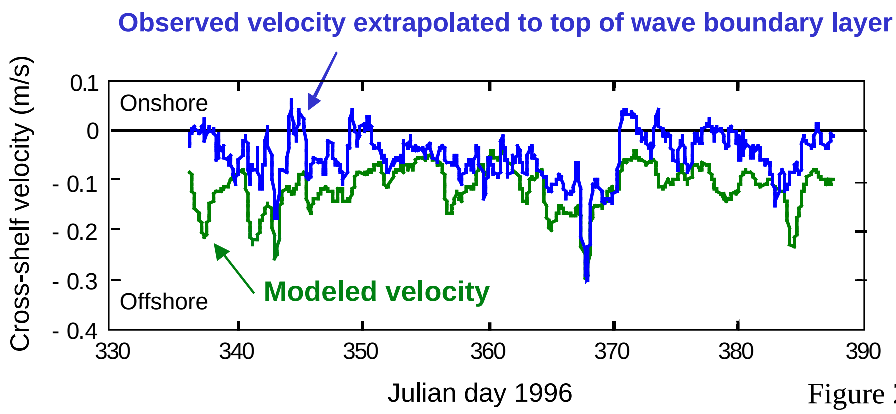

Figure 2

Use of Maximum Load Relation to Predict 1995 and 1997 Flood Deposits:

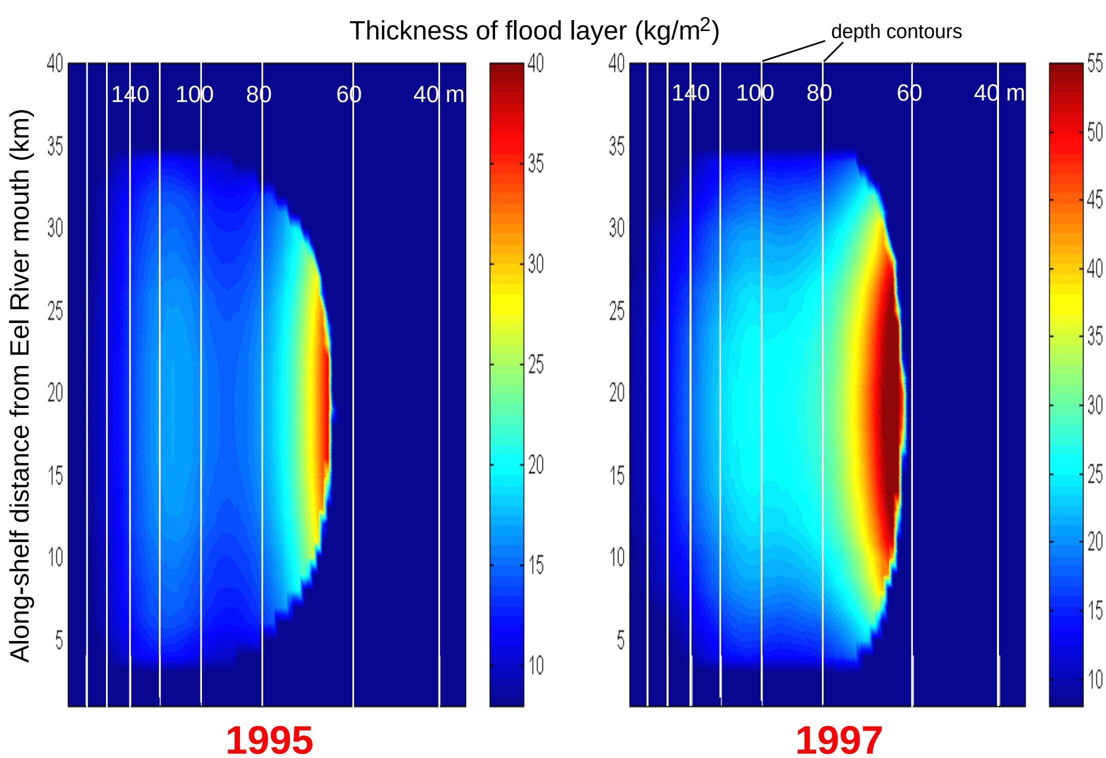

Figure 3

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